Time-dependent energetic laser-ion acceleration by strong charge separation field

Yongsheng Huang,[1,2,*] Yuanjie Bi,[1,2] Naiyan Wang,[1] Xiuzhang Tang,[1] and Zhe Gao[2]

[1]*China Institute of Atomic Energy, Beijing 102413, China.*

[2]*Department of Engineering Physics, Tsinghua University, Beijing 100084, China.*

(Dated: December 18, 2008)

Abstract

The laser-ion acceleration in the ultra-short and ultra-intense laser-matter interactions attracts more and more interest nowadays. Since electrons gain relativistic energy from laser pulse in a period of several femtoseconds and driven away by the ponderomotive force of laser pulse, a huge charge-separation field pulse is generated. In general cases, the ion acceleration is determined by this charge-separation field. A novel general time-dependent solution for laser-plasma isothermal expansions into a vacuum with different types of the scale length of the density gradient which correspond to different charge separation forms is obtained. The previous solutions are some special cases of our general solution. A series of new solutions have been proposed and may be used to predict new mechanisms of ion acceleration. However, many unaccounted idiographic solutions that may be used to reveal new acceleration mode of ions such as shock wave acceleration, may be deduced from our general solutions.

PACS numbers: 52.38.Kd,41.75.Jv,52.40.Kh,52.65.-y

[*]Electronic address: huangyongs@gmail.com

I. INTRODUCTION

The generation of energetic proton and acceleration mechanisms in the ultra-intense laser pulses interaction with thin targets attract more and more interest nowadays [1, 2, 3, 4, 5]. Their progress can provide fundamental theory for inertial confined fusion (ICF) and promote the realization of it effectively. The ultra-short and energetic ion beam allows for an increase of energy resolution in the Time Of Flight experiments, the investigation of the dynamics of nuclear processes with high temporal resolution and the study of spallation-related physics[6].

When a relativistic laser pulse interacts with a plasma, the laser-produced fast electrons with a unique temperature, $k_B T_e$, determined by the laser ponderomotive potential are instantly created and then driven away. However, the ions are still resting due to the large mass and then a high charge separation field generates. Furthermore, the plasma is assumed isothermal since the continuous energy supply of the laser pulse in the pulse duration. No matter proton shock acceleration (PSA)[7] in laser-plasma interactions or target normal sheath acceleration (TNSA)[4, 5, 8, 9] and so on, the ions are accelerated by high charge-separation field. The key point of ion acceleration is the hot-electron density distribution which decides the spatial and temporal distribution of the charge-separation field.

In this paper, a general solution for plasma isothermal expansions into a vacuum is proposed with the assumption: the ion density distribution can be represented a function with separable variables in the transformation system. With the solution, the separate charge distribution, electric field, electron velocity, ion velocity, and fronts of ions and electrons are all predicted. For different scaling length of the density, the solution corresponds to different expansion mode of plasmas. In some special cases, the solutions have been achieved by previous pursuers[5, 8, 10]. A series of new special solutions have been described and the corresponding acceleration modes have been discussed in detail. It is pointed out the shock wave forms for some types of the plasma density gradient and large scale length.

II. TIME-DEPENDENT ION ACCELERATION DUE TO STRONG CHARGE SEPARATION

For convenience, the physical parameters: the time, t, the ion position, l, the ion velocity, v, the electron field, E, the electric potential, ϕ, the plasma density, n, and the light speed, c, are normalized as follows: $\hat{t} = \omega_{pi0} t, \hat{l} = l/\lambda_{D0}, u = v/c_s, \hat{E} = E/E_0, \hat{\phi} = e\phi/k_B T_e, \hat{n} = n/n_{e0}, \hat{c} = c/c_s,$

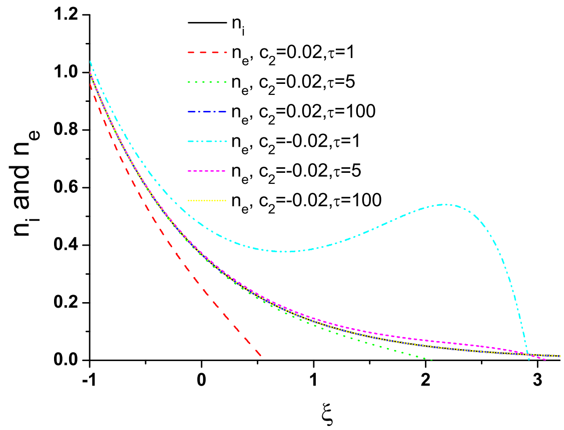

FIG. 1: (Color online) The ion velocity, n_i, and electron velocity, n_e VS the self-similar variable, ξ, for $L = -\beta_1 = -1$ and $N_1 \equiv 1$ in two cases: $u_0 = c_2 = 0.02$; $u_0 = c_2 = -0.02$.

where n represents n_i (or n_e) which is the ion (or electron) density, n_{e0} is the reference hot-electron density, $c_s = \sqrt{Zk_BT_e/m_i}$ is the ion acoustic speed, $\omega_{pi0} = \sqrt{Zn_{e0}e^2/m_i\epsilon_0}$ is the initial ion plasma frequency, $\lambda_{D0} = c_s\omega_{pi0}$, c is the light speed and $E_0 = k_BT_e/e\lambda_{D0}$. Here e is the elemental charge.

The reference frame used here is $\tau = \hat{t}, \xi = \hat{x}/\hat{t}$. With the transformation, the equations of continuity and motion are obtained easily in the new coordinate system. The ion density is assumed to satisfy: $n_i(\tau,, \xi) = N_1(\tau)N_2(\xi)$. Here, $N_1 \equiv 1$ corresponds the self-similar ion density and solution. If $N_2 = exp(-\xi/\beta_1 - 1)$, where β_1 is a constant, the self-similar solution is for a neutral-plasma isothermal expansion into a vacuum given by Huang *et al.* [5] for the impurity ions. $\beta_1 = 1$ corresponds the classic self-similar solution given by Mora in [8]. If $N_2 = n_0(\xi/\xi_0)^{-2/\alpha}$, where $\alpha \in (0, 2)$, the solution is for a half-self-similar non-neutral plasma isothermal expansion into a vacuum proposed by Huang *et al.* [10]. For $dN_1/d\tau \neq 0$, the analytic solution has not been reported. That is what given out by us next.

Combining the continuity and motion equation of ions gives the general solution of the ion velocity and potential in the ion region:

$$\begin{aligned} u_i &= \alpha_2(\xi) - \delta_1(\tau)\alpha_1(\xi), \\ \phi &= -\alpha_3^2/2 + \int[\alpha_3 + (\delta_1 + \delta_2)\alpha_1]d\xi', \end{aligned} \tag{1}$$

where $\delta_1 = \tau/L_\tau$, $\delta_2 = \tau^2/L_{\tau,2}$, $L_\tau = [\partial \text{ln} N_1/\partial\tau]^{-1}$ is the time scale length of the ion density, $N_1(\tau)$, $L_{\tau,2} = [\partial^2 \text{ln} N_1/\partial\tau^2]^{-1}$, $\alpha_1 = F\int F^{-1}d\xi'$ and $\alpha_2 = F\int F^{-1}\xi'/Ld\xi'$, $\alpha_3 = \delta_1\alpha_1 + \xi - \alpha_2$, $F = \exp^{-\int d\xi'/L}$ and $L = [\partial \text{ln} N_2/\partial\xi]^{-1}$ is the scale length of the time-independent ion density, $N_2(\xi)$. And the electric field is $E = -(\delta_1 + \delta_2)\alpha_1/\tau - \alpha_3^2/L\tau + \delta_1\alpha_3/\tau$.

Combining Eq. (1) and Poisson's equation, the electron density satisfies $n_e = n_i - \delta n$, where δn is decided by:

$$\delta n = \frac{2\alpha_3^2(1 + L^{'}/2)}{L^2\tau^2} - \frac{(2 + 3\delta_1)\alpha_3 - (\delta_1 + \delta_2)\alpha_1 - (\delta_1^2 - \delta_2)L}{L\tau^2}. \tag{2}$$

where $L^{'} = dL/d\xi$. From Eq. (2), $\lim_{\tau\to\infty} \delta n \to 0$ and it means that the plasma tends to neutral as $\tau \to +\infty$, whatever the initial state is.

We will confirm the ion front and electron front with physical discussions and on the bases of Poisson's equation and the continuity of the potential and electric field the next. The first case is the electron front is beyond the ion front. Therefore, beyond the ion front, the ion density is zero and it can be assumed that the expression of electron density is a smooth expansion with respect to self-similar variable, ξ. With the expression of electron density, solving the continuity equation of electrons, the electron density is $u_e = u_i + \delta u$, where δu satisfies:

$$\delta u = \frac{-\delta n\alpha_3 - (\partial\alpha_4/\partial\tau)/\tau + \alpha_4/\tau^2}{n_e} \tag{3}$$

where $\alpha_4 = (\delta_1 + \delta_2)\alpha_1 + \alpha_3^2/L - \delta_1\alpha_3$ and then $\tau\partial\alpha_4/\tau = (\delta_1 - \delta_2 - \delta_3 + \delta_1^2 + \delta_1\delta_2)\alpha_1 + 2\alpha_3(\xi - \alpha_2 - \delta_2\alpha_1)/L + (\delta_2 - \delta_1)\alpha_3$, and $\delta_3 = \tau^2\partial^3 N_1/\partial\tau^3$. In fact: $\delta n = -(\partial\alpha_4/\partial\xi)/\tau^2$. With Eq. (3), $\lim_{\tau\to+\infty} u_e \to u_i$.

Therefore, with the electron density and Poisson's equation, the electric field beyond the ion front satisfies:

$$E(\tau, \xi) = -\tau N_1 \int_{\xi_{i,f}}^{\xi} N_2 d\xi^{'} - \frac{\alpha_4(\xi)}{\tau}, \tag{4}$$

where $\xi_{i,f}$ represents the value of ξ at the ion front. In the ion region, the electric field is $E(\tau, \xi) = -\alpha_4(\xi)/\tau$. From Eq. (4), $\xi_{i,f}$, satisfies:

$$N_1 \int_{\xi_{i,f}}^{\xi_{e,f}} N_2 d\xi^{'} = -\frac{\alpha_4(\xi_{e,f})}{\tau^2}, \tag{5}$$

where $\xi_{e,f}$ stands for the position of the electron front there the electron density is zero.

With the expression of the ion front, $\xi_{i,f}$, maximum ion velocity is given by:

$$u_{i,m} = \alpha_2(\xi_{i,f}|_{\tau_{acc}}) - \delta_1\alpha_1(\xi_{i,f}|_{\tau_{acc}}), \tag{6}$$

where τ_{acc} is the acceleration time, which is about $1 - 2$ times of the laser pulse duration for the ion acceleration in the laser-solid interactions.

If the electron front is before the ion front, the ion velocity is larger than that of electrons. However, in reality, this situation can not happen. Therefore, we ignore the solutions in this case.

Before we discuss the different cases of the scale length, L, a very special solution that does not rely on the choose of L is given. If $N_1 \propto 1/\tau$, the special solution is:

$$n_i = n_e = \frac{N_2(\xi)}{\tau}, u_i = u_e = \xi, \phi = \phi_0, E = 0, \tag{7}$$

This solution corresponds a neutral plasma with no charge separation and a constant velocity expands into a vacuum.

In two special cases, the special solutions are familiar to us.

Case one: the scale length of ion density, L, is 0-degree polynomial in ξ, $L = -\beta_1$. If $L = -\beta_1$, $F = \exp^{\xi/\beta_1+1}$, $N_2 = F^{-1}$ and $u_0 = u(\xi = \xi_0)$ at $\xi_0 = -\beta_1$. Then $\alpha_1 = -\beta_1(1-c_1F)$, $\alpha_2 = \xi+\beta_1+c_2F$, $\alpha_3 = -\beta_1[1+\delta_1(1-c_1F)]-c_2F$ and $u_i = \xi+\beta_1+c_2F+\beta_1\delta_1(1-c_1F)$, where c_1 and c_2 are integral constants.

For $c_1 = 1$ and $c_2 = 0$, $u_0 = 0$. If $\delta_1 < \exp^{-\xi/\beta_1-1}$, ions are accelerated. Oppositely, if $\delta_1 > \exp^{-\xi/\beta_1-1}$, ions are decelerated. Therefore, as Huang *et al.*[4, 11] pointed out $\delta_1 \approx 1 > \exp^{-\xi/\beta_1-1}$ for $\xi \geq \xi_0 = -\beta_1$, this solution is not suitable to describe the ion acceleration in the ultra-intense laser-foil interactions.

For $c_1 = c_2 = 0$, a special solution: $\alpha_1 = -\beta_1$, $\alpha_2 = \xi+\beta_1$, $\alpha_3 = -\beta_1[1+\delta_1]$, $u_i = \xi+\beta_1+\beta_1\delta_1$ and $\delta n = 0$. Since $\alpha_4 = -\beta_1(1+\delta_2+2\delta_1)$, assuming $\xi_{e,f} = +\infty$, from Eq. (5), the ion front is

$$\xi_{i,f} = \beta_1 \ln\left(\frac{N_1\tau^2}{1+2\delta_1+\delta_2}\right) - \beta_1. \tag{8}$$

The main part of Eq. (8) is the similar as that given by Huang and co-workers[11] using physical discussion. This solution is a special time-dependent solution for neutral-plasma isothermal expansion into a vacuum given by Huang *et al.*[11]. In special case: $N_1 \equiv 1$, with Eq. (8), the ion front is governed by: $\xi_{i,f} = \beta_1[\ln(\tau^2)-1]$. Considering the initial conditions, the results given here are the same as that given by Huang *et al.*[5] and Mora [8] (where $\beta_1 = 1$). Huang *et al.* and Mora obtained the results through the physical discussion about the Debye length of electrons instead of analytic deductions. However, the same analytic method has been used by Huang *et al.*[10] to deduce a special result of the following solution in case two.

For $N_1 \equiv 1$, $u_i = \xi+\beta_1+c_2F$. With Eq. (2) and Eq. (3), $\delta n = -2c_2F(\beta_1+c_2F)/\tau^2$ and $\delta u = [(\beta_1+c_2F)^2(2c_2F+1/\beta_1)]/[\tau^2F^{-1}+2c_2F(\beta_1+c_2F)]$. For $u_0 = c_2 = 0$ ($\xi_0 = -\beta_1$), $\delta n = 0$ and the solution corresponds the general self-similar solution for neutral-plasma isothermal expansions into a vacuum pointed out by Huang *et al.*[5]. However, if $u_0 = c_2 > 0$ ($\xi_0 = -\beta_1$), the acceleration described by the solution , which is not for a neutral-plasma expansion, is more efficient than the

classic solution. If $u_0 = c_2 < -\beta_1$ ($\xi_0 = -\beta_1$), the ion will be accelerated in the opposite direction. If $-\beta_1 < u_0 = c_2 < 0$ ($\xi_0 = -\beta_1$), the ion will be accelerated first and decelerated then. The density distributions for $c_2 > 0$ and $c_2 < 0$ have been shown by Fig. 1.

Fig. 1 shows: $u_0 = c_2 = -0.02$ and the electron density is smaller than the ion density for $\xi < 3$ and the ion acceleration is less efficient than that in the neutral-plasma case; $u_0 = c_2 = 0.02$ and the electron density is larger than the ion density for all ξ and the ion acceleration is more efficient than that in the neutral-plasma case, since the hot-electron number is so much more than that of ions. In these two cases, the density difference becomes small with the increase of τ and tends to zero as $\tau \to +\infty$. The electron front is determined by: $u_e(\xi_{e,f}) \approx \hat{c}$ in the relativistic laser intensity. Then, with $\xi_{e,f}$, the ion front can be obtained by Eq. (5).

For $c_2 = 0$, it is equivalent to: $\xi_{e,f} + \beta_1 + \beta_1 \exp(\xi_{e,f}/\beta_1 + 1)/\tau^2] \approx \hat{c}$. With this, the electron front satisfies: $\xi_{e,f} < \hat{c} - \beta_1(1 + \exp(1)/\tau^2)$. However, in previous works given by Mora [8] and Huang and co-workers [5], the electron front is taken as the positive infinity. Then, with $\xi_{e,f}$ and Eq. (5), the ion front can be obtained by: $\xi_{i,f} = \beta_1 \ln[\tau^2/(1+\beta_1')] - \beta_1$, where $\beta_1' = \beta_1/(\hat{c} - \xi_{e,f} - \beta_1)$.

Case two: L is an one-degree polynomial in ξ, $L = -\alpha\xi/2$ and $\alpha \in (0, 2)$. In this case, $F = |\xi/\xi_0|^{2/\alpha} = \bar{\xi}^{2/\alpha}$, $\alpha_1 = -\beta\xi_0(\bar{\xi} + c_1 F)$, $\alpha_2 = (1+\beta)\xi_0(\bar{\xi} + c_2 F)$, $\alpha_3/\xi_0 = -\beta\bar{\xi}(1+\delta_1) - [\delta_1\beta c_1 + (1+\beta)c_2]F$, where $\beta = \alpha/(2-\alpha)$, c_1 and c_2 are integral constants. With Eq. (1), $u_i/\xi_0 = \bar{\xi}[1 + \beta(1+\delta_1)] + [\delta_1\beta c_1 + (1+\beta)c_2]F$. With this, the ion acceleration is determined by the initial state and the density distribution (neutral or not).

For $u_0(\xi = \xi_0) = 0$, $c_1 = c_2 = -1$, and the ion velocity is $\bar{\xi}\xi_0[1 + \beta(1+\delta_1)](1 - \bar{\xi}^{1/\beta}) < 0$ for $\xi > \xi_0 > 0$, $u_i = 0$ for $\xi = \xi_0$, and $u_i > 0$ for $0 < \xi < \xi_0$. All the ions move to the central point: $\xi = \xi_0$, and the farther the distant, the larger the ion speed. With Eq. (2), the density difference, δn, is calculated for $N_1 \equiv 1$. In this case, the electron front is given by $\delta n(\xi_{e,f}) = \bar{\xi}_{e,f}^{-2/\alpha}$. With Eq. (5), the ion front is obtained. Fig. 2(a) shows the ion and electron density at $\tau = 1$ and $\alpha = 0.5, 1, 1.5$. The ion and electron front are all obtained. This situation is not an efficient acceleration mode since maximum ion velocity for any $\alpha \in (0, 2)$ is very finite as shown by Fig. 2(b).

However, if $c_2 = 0.02$ and $N_1 \equiv 1$, the ion velocity is $\bar{\xi}\xi_0[1 + \beta(1+\delta_1)](1 + 0.02\bar{\xi}^{1/\beta})$. Fig. 3 shows the ion acceleration is efficient in this case, especially for $\alpha = 1.5$ and $\xi_0 = 1$. The electron and ion front are obtained with $n_e(\xi_{e,f}) = 0$ and Eq. (5) and shown by Fig. (3)(a).

For $c_1 = c_2 = 0$, $u_i = \xi + \beta\xi(1+\delta_1)$and $\phi = -(1+\beta)\beta\xi^2(1+\delta_1)^2/2 - (\delta_2 - \delta_1^2)\beta\xi^2/2$. $\delta n = [\beta\delta_2 + \beta^2\delta_1^2 + \beta(1+\beta)(2\delta_1 + 1)]/\tau^2$ This solution is also time-dependent and can be used to describe the energetic ion acceleration with an enhanced electron tail. For $N_1 \equiv 1$, the solution has

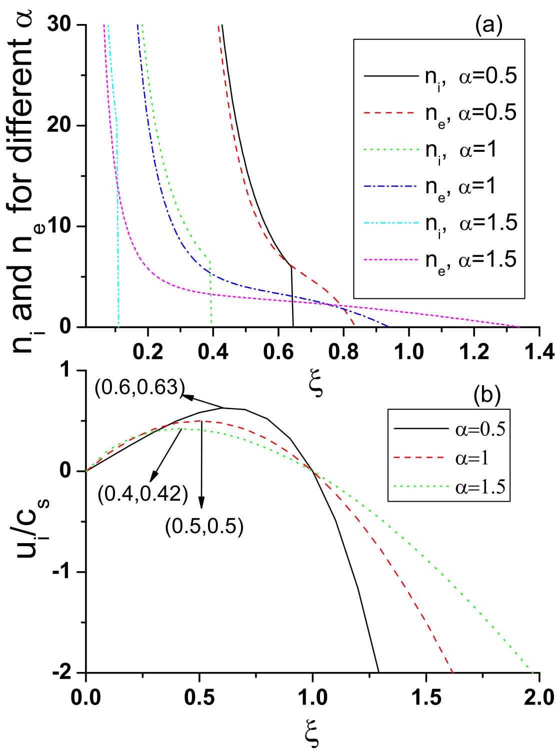

FIG. 2: (Color online) (a) The electron and ion density VS the self-similar variable, ξ, for $L = -(\alpha/2)\xi$ in three cases: $\alpha = 0.5, 1, 1.5$. The electron fronts are all before the ion fronts. (b) The ion velocity VS the self-similar variable, ξ, for $L = -(\alpha/2)\xi$ and $\alpha = 0.5, 1, 1.5$. In Fig. 2(a) and (b), $u_0(\xi = \xi_0) = 0$, $c_1 = c_2 = -1$, $\xi_0 = 1$, $N_1 \equiv 1$.

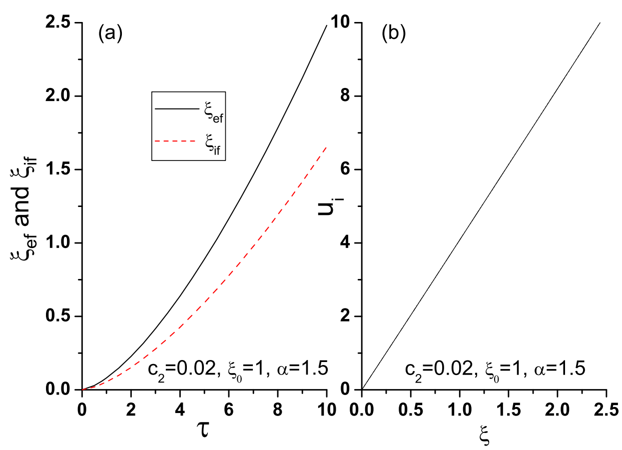

FIG. 3: (Color online) (a) The ion and electron front VS the expanding time, τ; (b) the ion velocity VS the self-similar variable, ξ, for $L = -\beta\xi/2$ and $N_1 \equiv 1$. Here, $c_2 = 0.02$, $\alpha = 1.5$ and $\xi_0 = 1$. The ion is accelerated efficiently and about 6 times acoustic velocity at $\tau = 10$.

been obtained by Huang *et al.* [10]. $\alpha_4 = -[\delta_2 + \beta(1+\delta_1)^2 + 1 + 2\delta_1]\beta\xi$ and $\xi_{i,f} = (\alpha/2)^{\beta}\xi_{e,f}$, and the electron front is given by:

$$\xi_{e,f} = \{\frac{N_1 n_0}{[\delta_2 + \beta(1+\delta_1)^2 + 1 + 2\delta_1]\beta}\}^{\alpha/2}\tau^{\alpha}. \tag{9}$$

In special case: $N_1 \equiv 1$, the results from Eq. (9) are the same as that obtained in [10].

Two special cases: L are zero-degree and one-degree polynomials in ξ have been calculated and some time-independent solutions are the same as the previous works. For different L, the ion accelerations are different. The key variable is the scale length of the time-independent electron density, L. In the neutral-plasma case, $L = -\beta_1$ ($\beta_1 \in (0,1)$), which is a zero-degree polynomial in ξ. In the hot-electron-tail case, $L = -(\alpha/2)\xi$ ($\alpha/2 \in (0,1)$), which is a one-degree polynomial in ξ. Even for the same L, different integral constants induce different solutions. However, the essential determinant is the charge separation: δn. Therefore, it is concluded that the charge separation of a plasma determines the ion acceleration.

Here, the case: L is a quadratic polynomial in ξ, $-\beta_2\xi^2$ ($\beta_2 \in (0,1]$), is considered the first time. For a n-degree polynomial: $L = -\beta_n\xi^n$ can be considered in the same way.

If $L = -\beta_2\xi^2(\beta_2 \in (0,1])$ and $N_1 \equiv 1$, $F = \exp(-1/\beta_1\xi + 1/\beta_1\xi_0)$, $n_i = F^{-1}$ and $u_i = \alpha_2 = F\int_{\xi_0}^{\xi} F^{-1}d\xi' + u_0 F$, where $u_0 = u_i(\xi = \xi_0)$ is a constant. With this, $\alpha_3 = \xi - \alpha_2$, $\alpha_4 = -(1-\alpha_2/\xi)^2/\beta_2$, $\delta n = 2(1-\alpha_2/\xi)(1+\beta_2\alpha_2 - \alpha_2/\xi)/\beta_2^2\tau^2$. Since $\lim_{\xi\to+\infty}\alpha_2 \to \xi + u_0\exp(1/\beta_2\xi_0)$, some results are obtained: $\lim_{\xi\to+\infty} u_i \to \xi + u_0\exp(1/\beta_2\xi_0)$, $\lim_{\xi\to+\infty}\alpha_3 \to 0$, $\lim_{\xi\to+\infty}\alpha_4 \to 0$ and $\lim_{\xi\to+\infty}\delta n \to 0$, $\lim_{\xi\to+\infty} n_i \to n_e$. With Eq. (5), the ion front and the electron front are all positive infinity. However, $\partial u_i/\partial\xi < 0$ for any u_0 and ξ large enough. Therefore, the shock wave forms for ξ large enough in this case.

Similar with above discussion, for $L = -\beta_n\xi^n$, the physics of the expansions of plasmas can be obtained easily and the same results of them are: the plasma front is positive infinity and the boundary condition should be added exteriorly. In fact, it is easy to prove that the analytic form of the solutions can not be obtained and they may correspond to shock section for $L = -\beta_n\xi^n, n \geq 2$ and ξ large enough.

It is required that $\partial L/\partial\xi < 0$ and $L \neq -\beta_n\xi^n, n \geq 2$ in order to make the limitation of the plasma density be finite as ξ tends to positive infinity. $L = -\beta_1$ and $L = -\alpha\xi/2$ are two simple cases.

In order to show time-dependent solutions, it ia assumed that $N_1 = \kappa\tau \propto \tau, \tau \in [0, \tau_u]$ as an example in two cases: $L = -\beta_1$ and $L = -\alpha\xi/2$. $N_1 = \kappa\tau$, then $\delta_1 = 1$ and $\delta_2 = 0$. For $L = -\beta_1$ and $c_1 = c_2 = 0$, $u_i = \xi + 2\beta_1$ and $u_{i,f} = \beta_1\ln(\kappa\tau^3 e/3)$, where $e = 2.718....$ For $L = -\alpha\xi/2$ and

$c_1 = c_2 = 0$, $u_i = (1 + 2\beta)\xi$ and $\xi_{e,f} = [\kappa n_0/(4\beta + 3)\beta]^{\alpha/2}\tau^{3\alpha/2}$. Considering the dependence of the electron density on τ described by Huang *et al.*in [4], these solutions can be used to describe the influence of the hot-electron recirculation on the ion acceleration at the rear of the target heated by ultra-intense laser pulse. Similar with above discussions, the ion front and electron front in the general case can also be obtained. Here, it is not repeated again.

III. CONCLUSION

In conclusion, a general time-dependent isothermal expansion for the ion acceleration due to charge separation is proposed on the base of the equations of continuity and motion of ions and Poisson's Equation. As examples, several new solutions for each types of the plasma density gradient have been proposed. Especially, for $L = -\beta_n\xi^n, n \geq 2$ and ξ large enough, we pointed out that the shock wave solution exists. However, the analytic formation can not be achieved easily here.

This work was supported by the Key Project of Chinese National Programs for Fundamental Research (973 Program) under contract No. $2006CB806004$ and the Chinese National Natural Science Foundation under contract No. 10334110.

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